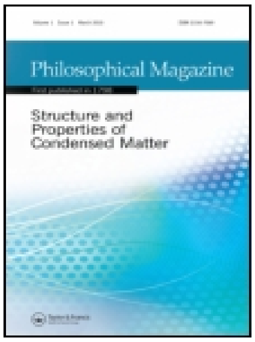

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The Motion of a Wire Through Ice

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Abstract

The rate of motion of a loaded wire through ice has been measured as a function of temperature. The experiments show that a finite motion is still present at temperatures which exclude the possibility of pressure melting. Reasons are advanced which suggest that the explanation of this behaviour may be associated with a surface film between the ice and the wire.

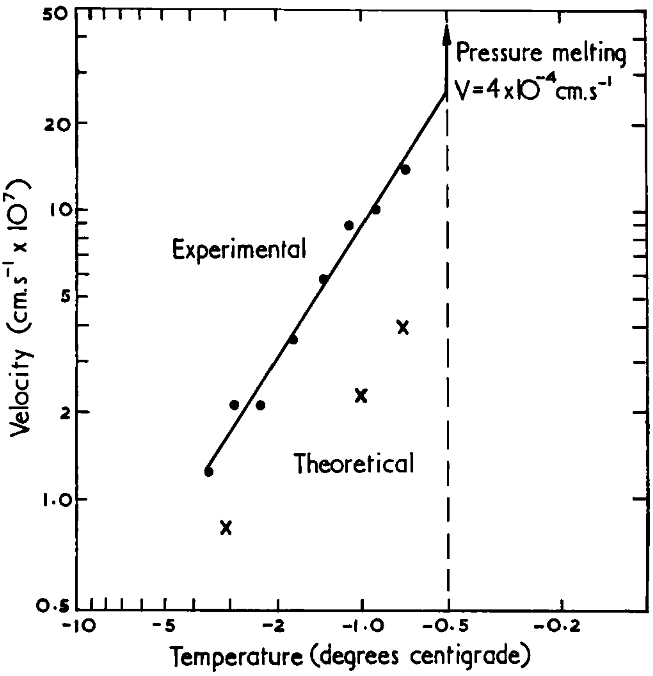
The explanation of the phenomenon of regelation has been in dispute since the introduction of the term by Tyndall (1858). He and Faraday (1859) attributed the effect to a thin layer of water on the surface of the ice, but this view was attacked by J. Thomson (1859) and W. Thomson (1858) who suggested the alternative of pressure melting. More recently the water layer idea has received support from the theory of Weyl (1951), and Fletcher (1962) has now gone further and predicted the temperature dependence of the film thickness.

Few quantitative experiments have been reported which have attempted to measure changes with temperature, or which can even clearly distinguish between the two mechanisms. In a common form of the regelation experiment used to demonstrate the effect qualitatively, a weight is hung on a thin wire strung across the top of a block of ice. The interpretation of the results of such experiments is often difficult because of poor temperature control, and in particular the flow of heat along the wire from the environment could often lead to local temperature rises near the wire, even though the bulk of the ice is at a known low temperature. The experiments to be described here use essentially the same geometry as this, but with a greater control of the relevant variables.

A block of ice about 1 cm thick was mounted vertically on a solid base. A steel wire 0·045 cm in diameter was stretched across a heavy frame, which was pivoted freely in ball races attached to the base so that the wire could move through the ice perpendicular to its length, but with no other degrees of freedom. The motion of the wire was measured by means of a contact wiping on a fixed length of platinum wire used as a potentiometer in a bridge circuit. The position was continuously recorded on a chart recorder with a sensitivity of about 1 cm on the chart for 0·004 cm movement of the wire. The whole device was contained in a cold box, and the temperature measured using a thermocouple soldered to the cutting wire very close to the block of ice ; this was also recorded continuously. During the measured runs the temperature in the box drifted by only 0·02°c per hour, and the recorded temperature is therefore believed to be characteristic of the interface between the steel wire and ice.

Most of our experiments have been carried out with a fixed load on the wire of 2·1 kg, and a small range of block thickness with a mean of 1·0 cm. (Some variation in thickness was unavoidable because of slow sublimation from the block, and this is probably the major source of experimental error.) The velocity at which the wire sinks through the ice has been measured with various temperatures for four blocks and the mean results averaged over small temperature intervals are shown in fig. 1. The accuracy of individual velocity measurements is better than 5%.

Fig. 1



Showing the measured mean velocities of passage of a steel wire through ice as a function of temperature. Wire diameter 0·045 cm, load 2·1 kg, thickness of block 1·0 cm. At the temperature marked by the arrow the velocity changed discontinuously by a factor of 200 due to pressure melting. Theoretical values of the rate according to Fletcher are also plotted.

The line fitting these points shows a strong dependence on temperature, with the rate increasing by a factor of 10 as the temperature increases from $-3{\cdot}5$°c to $-0{\cdot}7$°c, from about 10^{-7} cm sec^{-1} to 10^{-6} cm sec^{-1}. At a slightly warmer temperature there is a large discontinuous increase in the rate; as the temperature of the box was allowed to warm slowly through $-0{\cdot}5^{\circ}\text{C}$, there was an increase by a factor of 200. We attribute this sudden change to pressure melting. With our wire diameter and loading the pressure under the projected area of the wire in the block was about 45 atmospheres, and the lowering of melting point of half a degree is in good agreement with published values (e.g. see Dorsey 1940).

The motion, which is still observed at lower temperatures (and which would be completely missed without a sensitive recording system), can therefore *not* be attributed to pressure melting, but must be explained by some other mechanism. If we interpret the results in terms of the flow of a thin Newtonian shear layer of viscous fluid round the wire (as suggested by Fletcher's theory), then the measured velocity V may be shown to be related to the thickness d and viscosity η of this layer by:

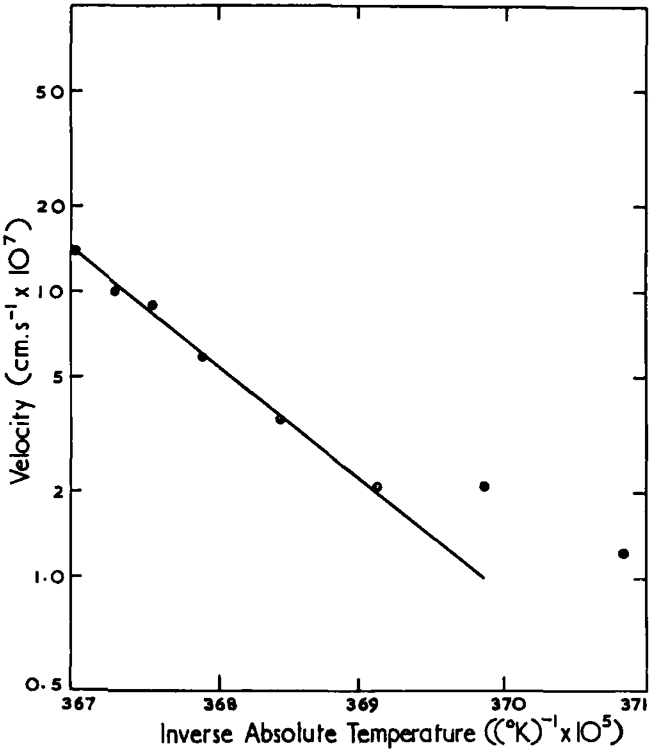
$$V=\frac{F}{12\pi\eta}\left(\frac{d}{a}\right)^3, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where F is the force per unit length of wire and a is its radius. The velocity variation with temperature might therefore be explained by a change in layer thickness with temperature in the sense predicted by Fletcher. If we insert his values of d, and the value of η appropriate to supercooled water in (1) we obtain the points marked by crosses in fig. 1 (Fletcher, private communication). The order of magnitude of the measured velocities and the variation with temperature seem to be well represented by this theory, though the assumption of Newtonian flow in the layer makes an exact comparison difficult, as the following considerations show this to be invalid.

A difficulty with this interpretation becomes apparent when we change the load on the wire. Increase in loading does not increase the rate of travel linearly ; a change of 50% in F gave three times the rate, so that V is approximately proportional to F^3. This result is similar to that found by Glen (1955) for a compression specimen of ice subject to polycrystalline creep, and it raises the question whether creep could account for our measurements. While it is not unlikely that Fletcher's fluid surface layer should exhibit non-Newtonian properties, further consideration is necessary to clarify the extent to which the movement is associated with extensive distortion of the ice. It is not possible in this type of experiment to distinguish between the type of creep where only the more highly stressed ice near the wire is able to diffuse around it, and a thin liquid layer. However, a comparison of the rate of movement of the wire with the inverse of absolute temperature leads to a significant difference. As discussed on page 532 of Glen's (loc. cit.) paper, his results lead to an activation energy of 31·8 kcal/mole. Figure 2 shows the same plot for our results and we derive 180 kcal/mole from the line fitting the warmer temperatures. Thus the mechanism in our case does not seem to be the normal creep process.

The following observations support the above viewpoint in so far as they show the extensive release of stress by creep in the bulk of the ice to have been unlikely. Firstly, the crystals in the slowly grown ice blocks used were probably much larger than the wire moving through them, so that at any time only a few crystals are being affected. Secondly, we froze a block round a narrow straight strip of gold leaf (so thin that it was not fully opaque to light) and observed directly the distortion of the leaf after the wire had passed through it. The edges of the track were extremely sharp, with the final displacement less than 0·2 of the wire diameter at the edge of the track and no apparent distortion or breaking of the foil further away. Although no theoretical solution is available for viscous or plastic flow round a cylinder, Darwin (1953) has calculated the nature of the distortion of an originally plane layer of fluid in potential flow, and this should give a lower limit to the corresponding effects in plastic flow. The actual displacement at the edge of the track of the cylinder in Darwin's case is about 0·4 radii, and there is severe local stretching during the passage of the cylinder which should have led to breaks in the foil if they had occurred in our case. The velocity field in the viscous case falls off much more slowly, and we would thus expect the effects to extend even further into the ice than Darwin's

Fig. 2



This plot shows that, except for the two coldest points, the solid equation of state is obeyed. This is of the form $v = v_0 \exp(-Q/RT)$. Here $Q = 180$ kcal/mole. The two points not on the line correspond to the smallest velocities and are likely to have greater experimental error.

calculation indicated. Since no distortion was observed, we can have more confidence that the explanation in terms of effects very close to the wire is the correct one.

To summarize, our experiments therefore show that pressure melting cannot always account for phenomena usually described by the term regelation, and that the existence of a thin fluid layer on the surface of ice seems a likely explanation for the continued passage of a loaded wire through ice at temperatures lower than those at which pressure melting could be effective.

ACKNOWLEDGMENT

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